

Tympanic Membrane Perforation and Hearing Loss From Blast Overpressure in Operation Enduring Freedom and Operation Iraqi Freedom Wounded

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Background: Tympanic membrane perforation is the most common primary blast injury in the current conflicts and occurs in approximately one tenth of service members wounded by combat explosions. We wanted to determine the severity of perforation and its effect on hearing and combat readiness.

Methods: This analysis is a retrospective study of US service members injured in combat explosions in Afghanistan or Iraq and treated at our institution between March 2003 and July 2006. Data captured included location and grade of perforation, symptoms, healing rates, audiogram results, need for hearing aids, and loss of eligibility for military service.

Results: Of 436 explosion-wounded patients admitted to our facility, 65 (15%) patients had tympanic membrane perforation diagnosed by the otolaryngology service. A total of 97 tympanic membrane perforations occurred among 65 patients. The average surface area involved was $41\% \pm 32\%$ (right) and $35\% \pm 34\%$ (left). More than one third of perforations were grade 4. The most common locations were central and anterior-inferior. Most (83%) patients reported symptoms, most commonly diminished hearing (77%) and tinnitus (50%). Outcome data were available for 77% of perforations. Spontaneous healing occurred in 48%. The remainder

(52%) had surgical intervention. The most common audiogram abnormality was mild high frequency hearing loss. Ultimately, three patients (5%) required hearing aids and one discharge from military service.

Conclusions: Tympanic membrane perforation occurs in 16% of explosion-injured patients. Most patients are symptomatic and many have large perforations requiring operative intervention. Long-term hearing loss is uncommon but does impact ability to continue military service.

Key Words: Blast, Improvised explosive device, Explosion, Ears, Hearing, Tympanic membrane, OEF, OIF.

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Primary blast injury is tissue destruction caused by the blast wave of high-pressure air that travels outward from an explosion. Tympanic membrane (TM) rupture is the most common form of primary blast injury. Since the ear is, by design, the body's most sensitive pressure transducer, it is the organ most commonly affected by the dramatic changes in ambient air pressure that occur close to an explosion.¹ Studies of service members injured in combat have demonstrated that TM perforation occurs in approximately 9% of patients wounded by explosives. (Ritenour AE, Blackbourne LH, Kelly JF, et al. Primary blast injury in OEF/OIF: 2003–2006. Unpublished data.) TM rupture occurs more frequently when an explosion takes place in a closed space and when victims are in close proximity to the detonation center.² The lowest pressure necessary to perforate a TM is about 5 psi³; approximately 50% of TMs will rupture at 15 psi.⁴ Various factors have proven to positively or negatively affect an individual's susceptibility to

TM rupture. Studies have demonstrated that disease or previous injury, increased age,⁴ inadequate pneumatization,⁵ and TM position perpendicular to the incident wave⁶ all increase the likelihood of perforation. Conversely, plugs of cerumen may exert a protective effect when loose in the external auditory canal, but may serve as a "ramrod" increasing injury if they are in contact with the TM at the time of the explosion.⁴ Simple ear plugs are very effective in reducing the incidence of TM rupture, but are impractical in situations, such as combat, where accurate understanding of quiet verbal communication is critical.⁷

Investigators have demonstrated that up to 80% of all perforated TMs heal spontaneously with relatively few requiring operative intervention.⁸ Large size of perforation (high grade)⁹ and peripheral location of the defect have both been associated with lower rates of spontaneous healing.¹⁰ Most patients, in previous studies, were reported to be asymptomatic or presented with subjective hearing loss and tinnitus.⁸ Many patients have acute hearing deficits that quickly resolve when they are allowed to recover in a quiet environment,¹¹ which may be impossible in the combat theater. The most common permanent audiogram finding among patients with TM rupture from explosions is mild high frequency sensorineural hearing loss.^{12–15} Hearing impairment can inhibit a service member's ability to detect enemy movement and may render personnel more of a combat liability than an asset.¹⁶

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In a recent review of primary blast injury in Operation Enduring Freedom (OEF) and Operation Iraqi Freedom (OIF), investigators found that 9% of all US military personnel that receive in-patient care for explosion injuries have TM perforation. (Ritenour AE, Blackburne LH, Ritenour JS, et al. Incidence of primary blast injury among service members injured in combat explosions. Unpublished data.) Additionally, a review of explosion-injured patients treated at our institution revealed that TM rupture is even more frequent among US service members who have suffered burns in an explosion. (Ritenour AE, Blackburne LH, Ritenour JS, et al. Incidence of primary blast injury among service members injured in combat explosions. Unpublished data.) These studies prompted us to closely review our experience with TM perforations caused by explosions to determine associated mechanism of explosive injury, rate, grade and location of perforation as well as symptoms and outcomes such as spontaneous healing and permanent hearing impairment.

METHODS

The US Army Institute of Surgical Research (USAISR) Burn Center, resides within Brooke Army Medical Center (BAMC) at Fort Sam Houston, TX and is the only referral center for combat-wounded US military personnel who require specialized burn care. This American Burn Association-verified burn center receives approximately 3% of all combat wounded service members. BAMC, an American College of Surgeons designated Level I trauma center, receives approximately 10% of all US combat casualties. Both institutions maintain databases on all burn and trauma admissions. These databases include information on injury patterns and severity, medical care and outcomes. After approval from the BAMC or USAISR institutional review board, these databases were used to compile a list of service members with TM perforation from combat explosions during OIF and OEF treated at the USAISR or BAMC between March 2003 and July 2006. The diagnosis of TM rupture was determined by otoscopic examination of the TM by the otolaryngology service or the admitting service. Information from the patients' electronic in-patient and outpatient charts was used to construct a study database using Excel (Microsoft, Redmond, WA). Demographic data, mechanism and date of injury, percent of total body surface area (%TBSA) (if applicable), grade, location and symptoms of TM rupture were collected. A grade 1 perforation was defined as a pinpoint or linear tear up to 2 mm, grade 2 involved <25%, grade 3 involved 25% to 50%, and grade 4 >50%. Outcomes data of rates of healing and surgical intervention as well as audiogram data were also collected. Military personnel who were killed in action or who did not survive transfer to the San Antonio were not included. Data are reported as mean \pm SD or as raw numbers with associated percentages.

RESULTS

Demographics

During the inclusion period, 466 US military service members injured in combat were admitted to BAMC or USAISR, of which 436 patients had been injured in explosions. Of these patients, 69 had a documented TM perforation. The 65 (15% of all explosion-injured patients) that had been evaluated by the otolaryngology service were included in our study. Sixty (92%) were men; five (8%) women. The average age was 27 years \pm 7 years (range, 19–48 years). Fifty-nine (91%) of the patients had burns with an average %TBSA of 9% \pm 11%, (range, 1%–49%). Most patients had smaller burns, with only nine patients (14% of the study population) having \geq 20% TBSA burn.

TM Perforation

The incidence of TM perforation was 16% or 69 of 436 explosion-injured in-patients. Sixty-five patients (94%) had evaluations by the otolaryngology service and had detailed descriptions of the perforations and clinical course data available. These patients were used for the following data collection and analysis. A total of 97 TM perforations were found in 65 patients, 32 patients (49% of the study population) had both TMs ruptured. The average percentage of the TM surface area involved was 47% \pm 30%, range 5% to 90% bilaterally. In our series 40% of ruptured TMs were grade 4. Figure 1 summarizes the distribution of grade of perforation. Location of perforations data were available in 85 of 97 (88%) of involved ears. The most common locations were central and anterior-inferior. Location of perforations is summarized in Table 1. Most (83%) patients reported symptoms, most commonly diminished hearing (77%) and tinnitus (50%). Table 2 summarizes symptoms at the time of initial evaluation by the otolaryngology service. Follow up documenting resolution of perforation was available for 76% (74 of 98) of perforations. Of these, spontaneous healing occurred in 46%. As the grade of perforation increased the spontaneous healing rate decreased from 100% in the few ears with grade 1 perforations to 11% in ears with grade 4 perforations. Table 3 summarizes the relationship between grade and healing rate.

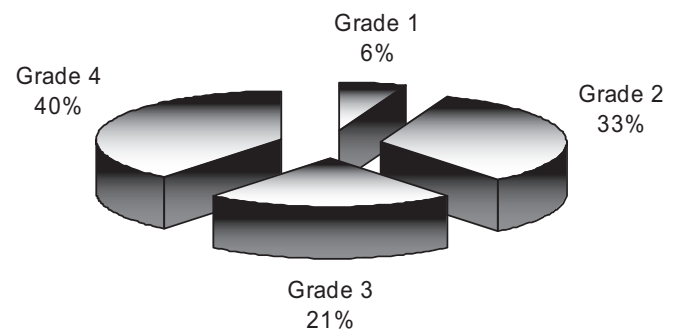


Fig. 1. Distribution of grade in 97 TM perforations in 65 patients.

Table 1 Distribution of the Location of TM Perforation in 97 Ears Ruptured by Combat Explosions

Location of Perforation	No. of Perforations	Percent
Central	33	34
Anterior	10	10
Anterosuperior	3	3
Anteroinferior	15	15
Posterior	10	10
Posterosuperior	1	1
Posteriorinferior	5	5
Superior	0	0
Inferior	5	5
Not documented	15	15
Total	97	100

Table 2 Frequency of Symptoms Present in Patients With Explosion-Induced TM Rupture at the Time of Initial Evaluation by the Otolaryngology Service

Symptoms	No. of Patients	Percent of Patients
Decreased hearing	37	77
Otalgia	6	15
Aural fullness	5	19
Otorrhea	10	25
Tinnitus	21	50
Vertigo	3	8

Table 3 Grade of Tympanic Membrane Perforation, Size of Perforation, and Spontaneous Healing Rate

Grade	No. of TMs Perforated	Perforation (%)	No. With Outcome	Healed (%)	Surgery (%)
I	5	5 ± 0	3	100	0
II	28	17 ± 6	18	83	17
III	19	42 ± 8	15	33	67
IV	32	81 ± 11	27	11	89
Total (all TMs)	98	47 ± 30	74	46	54

Table 4 Audiogram Findings at Three Time Points for 65 Patients With TM Rupture From Explosions

Audiogram	Normal (%)	Hearing Loss (%) (% w/o prior HL)	No Audiogram (%)
Predeployment	37	32	31
Postinjury	11	80 (52)	9
Posthealing	9	51 (39)	40

Postinjury audiograms were the first audiograms taken after TM perforation. Posthealing audiograms were taken after healing of TM perforation and at least 6 mo after injury.

Audiogram Data

Audiogram data are summarized in Table 4. Predeployment audiograms were available for 69% of the patients and hearing loss was present in 32% before injury. After injury, 80% of patients had hearing loss on audiogram. Of these patients the most common audiogram abnormality was mild high frequency hearing loss. Ultimately, three patients (5%)

required hearing aids, one limited duty and one discharge from military service.

DISCUSSION

Interest in the effects of the blast wave has been renewed as the injury patterns during the current military conflict, as in previous conflicts, are mostly from explosions.¹⁷ An early OEF report of 41 patients injured by a Joint Defense Attack Munition bomb drop found a 17% incidence of TM rupture. Approximately 10% of the patients in this series had burns.¹⁸ Reviews of Marines injured in OIF have estimated the incidence of TM rupture to range from 7% to 13% among the wounded.^{19,20}

Our patient population reflects the male predominance, generally young age and frequent use of improvised explosive devices against US military personnel in combat theaters. Since the USAISR Burn Center is the only referral center providing specialized burn care for wounded service members, our study is representative of the patients with large or complex burns requiring specialized care. The spectrum of nonburned patients from OIF and OEF may not be adequately represented since we introduced a selection bias by performing a study of only those US military admitted to BAMC or the USAISR Burn Center. Potentially, the least and most severely injured patients were excluded from our study. Patients who were evaluated but not admitted to USAISR Burn Center or BAMC were not included. Additionally, casualties who died in theater or during transfer to the United States were not included. Although civilian studies have reported a higher rate of TM rupture in terrorist bombing victims, a recent review of over 4000 explosion casualties from OEF and OIF found a 9% incidence of TM rupture. (Ritenour AE, Blackburn LH, Kelly JF, et al. Primary blast injury in OEF/OIF: 2003–2006. Unpublished data.)

Previous studies have reported a wide range of incidences for TM rupture (9%–47%)^{21,22} among patients injured by explosion. The incidence of 17% TM rupture in our study is within the range of previous studies. A study of 147 patients with TM perforation during military service from 1967 to 1986 found that most perforations were lower grade (24% grade 1, 42% grade 2, 27% grade 3, and 7% grade 4).²³ In contrast, in our series, 40% were grade 4 perforations with only 6% grade 1. Our distribution of perforation grades was similar to those reported in the Kenya embassy bombing in which 40% were grade 4.²⁴ This may be a result of patients with larger, symptomatic perforations being more likely to seek medical care for aural symptoms or it may reflect the real distribution of TM perforation severity in our patient population.

Spontaneous healing rates after TM perforation range from 78% to 88%.⁸ Our low spontaneous healing rate (46%) may be attributable to high grade and central location. Previous studies have demonstrated an inverse relationship between grade and spontaneous healing rate. One study found that 92% grade 1 perforations spontaneously healed whereas only 20% of grade 4 perforations healed without surgical intervention.⁶ In another series, the author found that all

perforations that healed spontaneously involved <80% of the TM, and that all perforations that did not heal involved >80%.²⁵ This finding has led some authors to suggest that early operative intervention may be warranted in patients with large perforations that are unlikely to heal. Location of the perforation also affects healing rates. Inferior perforations, reportedly, have the highest spontaneous healing rate, with central kidney-shaped perforations having the lowest.²³ In our study, 33% of perforations were central, which may have contributed, in part to our low spontaneous healing rate.

The most common symptoms reported in patients with blast-induced aural injury are hearing loss, tinnitus, pain, and dizziness.⁸ Among 29 patients with hearing-related symptoms after a closed-space explosion, 67% had tinnitus, 55% had hearing loss, 41% had pain, 41% experienced dizziness, and 53% had discharge.²⁶ Similarly, in our series, the most common symptoms were hearing loss, tinnitus, and otorrhea. Whereas most patients (83%) had symptoms, 17% of patients with TM rupture were asymptomatic. Otoloscopic examinations should be routinely performed in all explosion casualties to diagnose, treat and provide continuing care of patients with aural injury. All patients, even those unaware of symptoms, should have audiometry performed.

Previous series have reported a 30% incidence of high frequency hearing loss (>30 dB at 4000 and 8000 Hz) that was still present 1 year after exposure to explosion.⁸ Hearing loss persisting for 6 months can be considered permanent.^{27,28} In our series, 5% had hearing loss severe enough to require hearing aids. In the communication-rich environment of the modern battlefield, impaired hearing may adversely affect a service member's duty performance. Ear plugs have been proven to lower overpressure in an ear canal model from 190 kPa to 14 kPa, making TM perforation unlikely.²⁹ Ear plugs should be worn when mission allows. Perhaps in the future more sophisticated ear plugs will permit transmission of speech frequencies while providing protection against high overpressures likely to cause aural injury.

CONCLUSION

TM rupture occurs in approximately 16% of inpatients wounded in combat explosions. More than one third of perforations were grade 4. The most common locations were central and anterior-inferior. Most patients reported symptoms, most commonly diminished hearing and tinnitus. Outcome data were available for 77% of perforations. Spontaneous healing occurred in 48% and surgical intervention in 52%. The most common audiogram abnormality was mild high frequency hearing loss. Ultimately, 5% required hearing aids and one discharge from military service.

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DISCUSSION

Dr. James S. McGhee (US Army Aeromedical Research Center, Fort Rucker, AL): CPT Ritenour's excellent and timely research draws attention to the problem of blast-induced ear injury in the military. Hearing is essential to situational awareness and effective communication on the battlefield. Exposure to combat noise degrades combat effectiveness, and causes acute and chronic acoustic injury. The US Army Center for Health Promotion and Preventive Medicine reports that more than 400,000 veterans received hearing disability benefits from the Department of Veterans Affairs in 2005. The cost of hearing loss and tinnitus disabilities for all veterans in 2005 exceeded \$1 billion.

This is a valuable article because its review of ototrauma in an important subpopulation of blast-exposed service members within the clinical spectrum of the larger set of blast-exposed individuals previously described in the literature. Differences between this severely burned blast population and the broader population are explainable. For example, the author points out that it is likely that the relatively low spontaneous tympanic membrane healing rate observed is due to the larger proportion of higher grade ruptures in this population.

Ritenour reports follow-up audiograms taken at least 6 months after injury showed a significant residual hearing threshold shift in the burned blast-exposed patients. This can be compared with the results of nonburn blast-exposed patients seen between 2003 and 2005 at the Walter Reed Army Medical Center Audiology Clinic. This population reported by Cave et al. sustained a 60% hearing loss with nearly 50% having a sensorineural component. Other characteristics of this group included a 32% incidence of tympanic membrane perforation, 49% with residual tinnitus, 26% with otalgia, and 15% reported dizziness. Neither age nor the presence of associated traumatic injury (including amputation, but not including burns) was shown to be a predictor of threshold level shift.¹

The article reports that the most common audiogram abnormality was mild high frequency hearing loss. Persaud, in his report of otologic trauma from a 1999 London nail bombing, observed high- and low-frequency decrements. The low-frequency threshold shift directly correlated to the grade of the tympanic membrane rupture and resolved with healing.

But the high-frequency hearing loss did not show such correlation. Further, high-frequency sensorineural loss was more common, more severe and more persistent. In this series, the 4 kHz dip in threshold usually associated with noise-induced hearing loss was not seen in this blast injury population.² High intensity noise causes more sensorineural damage than a single, high intensity blast.³ This suggests the possibility that blast damage occurs through a different mechanism than damage from chronic loud noise exposure. It is safe to say that the mechanisms of blast-induced injury to special sensory end organs or to the central nervous system are still not well understood.

Hearing loss due to acoustic trauma is a significant factor on the modern battlefield. A better understanding of the mechanisms of otologic injury will have important therapeutic implications, and one day could be instrumental to battlefield survival. Ritenour et al. have provided a description of the otologic effects of blast in a specific subset of the blast-exposed population, underscoring the importance of accurate and complete data collection to enhance our understanding of this threat. Future research will further elucidate the role of blast itself in the cause and mechanism of hearing loss.

Dr. Amber E. Ritenour (US Army Institute of Surgical Research, Fort Sam Houston, TX): Thank you, Dr. McGee, for your thoughtful comments. We hope that our research will serve to increase awareness of and screening for tympanic membrane rupture and hearing loss in explosion-injured patients. It is especially important in our patient population that relies on verbal communication to convey detailed instructions during combat. We recommend that all patients injured in explosions undergo otoscopic examination early in their treatment course. Audiograms should be performed when clinically feasible. Hopefully, technological advances in developing combat-compatible hearing protection will make TM rupture and hearing loss from battlefield explosions a pattern of injury no longer seen among US military service members. However, in the meantime, clinicians should remain vigilant in screening even most severely injured patients.

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